HYDRODYNAMICS OF CONVECTION UNDER WINTER POLAR LEADS

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by

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1. Introduction:

During the contract period, the principal investigator and his graduate associates Mr. C.Y.Ching and Ms. B. Ayotte worked on several problems related to lead-induced convection, and oceanic convection in general. The results of these studies are outlined below. Mr. Ching is in the process of finishing his Ph.D., and his thesis will be available as a report. Other relevant publications originated from the P.I.'s group during the contract period are listed at the end of this report.

2. Research on Oceanic Convection

Because of large space and time scales involved, oceanic convective motions (which may take the form of plumes and thermals) are expected to be influenced by the background rotation. These rotational effects may arise either due to the earth's rotation or due to the presence of a parent cyclone. Thus, the understanding of oceanic convection requires a good knowledge on the influence of rotation on convection from isolated sources.

(a) Plumes

If a point plume is released from a source placed within a fluid, in the absence of rotation, it will first accelerate to a maximum speed and then decelerate. If the source diameter of the plume is d_o, then it is possible to argue that its evolution will be governed by the total buoyancy defined as $B = \pi d_o{}^2 \beta_o u_o/4$, where β_o is the initial buoyancy, u_o is the initial velocity and d_o is the source diameter of the plume. Thus, it is possible to write the r.m.s. velocity u and the integral lengthscale ℓ of turbulence within the plume, at a distance z away from the source, as

$$u = \alpha_1 \left(\frac{B}{z}\right)^{1/3} f_1\left(\frac{d_o}{z}\right) , \tag{1}$$

and

$$\ell = z f_2\left(\frac{d_o}{z}\right) , \tag{2}$$

where $f_1, f_2 \ldots$ are functions and $\alpha_1, \alpha_2 \ldots$ are constants. For point plumes $d_o/z \to 0$, and it is possible to write

$$u = \alpha_1 \left(\frac{B}{z}\right)^{1/3} , \tag{3}$$

and

$$\ell = \alpha_2 \, z . \tag{4}$$

Further, the depth h to which the plume descends at a time t after the release can be written as

$$h = (Bt^3)^{1/4} f_3(d_o/(Bt^3)^{1/4}), \tag{5}$$

where purely dimensional arguments have been used. For point plumes (5) becomes

$$h = \alpha_3 (Bt^3)^{1/4}. \tag{6}$$

When the plume descends in a rotating fluid, it is expected that it will be influenced by Coriolis and centrifugal forces some time after the onset of the motion. Since the mean velocity of the plume is vertical (in the direction of the rotational vector), the rotational influence will act mainly on the plume turbulence rather than the mean vertical flow. Previous works of the P.I. have shown that the turbulence is affected by the background rotation when the inertia forces are of the same order as the Coriolis forces, viz.,

$$\frac{u^2}{\ell} \approx 2\Omega u\ , \tag{7}$$

or, when the turbulent Rossby number drops below a critical value,

$$Ro = \frac{u}{\Omega \ell} < Ro_{cr} = \alpha_4\ , \tag{8}$$

where Ω is the rate of rotation. Using (3), (4), and (8) for point plumes, the critical depth z_c where the rotational effects inhibit the growth of the plume can be written as

$$z_c = \left(\frac{\alpha_1}{\alpha_4 \alpha_2}\right)^{3/4} \left(\frac{B}{\Omega^3}\right)^{1/4} = \alpha_z \left(\frac{B}{\Omega^3}\right)^{1/4}\ . \tag{9}$$

Since the width of the plume b at $z < z_c$ can be written as

$$b = z\, f_4\left(\frac{d_o}{z}\right), \tag{10}$$

or for point plumes

$$b = \alpha_5 z, \tag{11}$$

the critical width of a point plume b_c at the onset of rotational effects is

$$b_c = \alpha_5 \left(\frac{\alpha_1}{\alpha_4 \alpha_2}\right)^{3/4} \left(\frac{B}{\Omega^3}\right)^{1/4} = \alpha_b \left(\frac{B}{\Omega^3}\right)^{1/4}\ . \tag{12}$$

Using (6) and (9), the time t_c for the onset of the rotational effects can be estimated as

$$\Omega t_c = \alpha_7\ . \tag{13}$$

In oceanic cases, the descending plumes eventually intersect with a horizontal boundary (say located at a distance H below the source), and it is instructive to consider the evolution of the plume once it impinges on the boundary and spreads horizontally as a gravity current. Two cases should be considered.

(a) The plume is not influenced by the rotation prior to the arrival at the boundary ($z_c >> H$); In this case, the plume parameters at the impingement can be calculated using the governing variables B, H, and d_o. For the simple case of a point plume, the buoyancy of the plume at the interface β can be written as

$$\beta = \alpha_4\left(\frac{B^2}{H^5}\right)^{1/3} , \qquad (14)$$

or for a plume with a finite diameter

$$\beta = \left(\frac{B^2}{H^5}\right)^{1/3} f_5\left(\frac{d_o}{H}\right) . \qquad (15)$$

Upon impingement, the resulting gravity current flows horizontally until the baroclinic instabilities are developed. The velocity of the gravity-current nose can be evaluated by a balance between horizontal pressure gradient forces and inertia forces as

$$c \sim \left(\beta h_g\right)^{1/2} , \qquad (16)$$

where h_g is the height of the gravity current. On dimensional grounds, for a point plume,

$$h_g \sim H \qquad (17)$$

and hence

$$c \sim \left(\beta H\right)^{1/2} . \qquad (18)$$

If one assumes that the gravity current becomes unstable and breaks into a number of eddies, whence it propagates to a radius r_c proportional to the Rossby radius of deformation c/Ω, it is possible to write

$$r_c = \alpha_g\left(\frac{B}{H\Omega^3}\right)^{1/3} , \qquad (19)$$

where α_g is a constant. On the other hand, if a plume with a finite source diameter d_o is considered, the dimensional arguments yield

$$\frac{r_c}{\left[\frac{B}{(H\Omega^3)}\right]^{1/3}} = f_6\left[\frac{d_o}{H}, \frac{H}{\left(\frac{B}{(\Omega^3)}\right)^{1/4}}\right]. \tag{20}$$

However, in the limit $d_o \rightarrow 0$, this should yield (19) and hence it is possible to argue that f_6 should be independent of $H/(B/\Omega^3)^{1/4}$, viz.,

$$\frac{r_c}{\left[\frac{B}{(H\Omega^3)}\right]^{1/3}} = f_7\left[\frac{d_o}{H}\right]. \tag{21}$$

(b) $z_c < H$: Since the plume growth is arrested by the rotation at z_c, it is possible to assume that the buoyancy at $z = H$ is the same as that at $z = z_c$. Using an expression equivalent to (14), it is possible to write

$$\beta \sim \left(B\Omega^5\right)^{1/4}, \tag{22}$$

and equivalent to (18),

$$c \sim \left(\beta z_c\right)^{1/2} \sim \left(B\Omega\right)^{1/4}. \tag{23}$$

Thus the radius at which the flow (gravity current) becomes unstable is given by

$$r_c \approx \alpha_{10}\left(\frac{B}{\Omega^3}\right)^{1/4}. \tag{24}$$

This suggests the possibility of the gravity current becoming unstable from the onset.

(b) Thermals

For thermals released from a point source, it can be shown that the governing parameter would be the total initial buoyancy q_T. Previous self-similarity arguments and laboratory experiments suggest that, in the absence of background rotation, the vertical distance traveled by the thermal h and its width b at any time t during the decelerating phase, should satisfy

$$h \approx c_1 q_T^{1/4} t^{1/2}, \tag{25}$$

$$b \approx c_2 h, \tag{26}$$

where c_1, c_2 are constants. Similarly, the turbulent quantities pertinent to a descending thermal can be written as

$$u \sim \frac{q_T^{1/2}}{z}, \tag{27}$$

and

$$\ell \sim z. \tag{28}$$

It is expected that the thermals feel the rotational effects when (8) is satisfied or when

$$z_c \approx c_3 \left(\frac{q_T}{\Omega^2} \right)^{1/4}, \tag{29}$$

and

$$b_c \approx c_4 \left(\frac{q_T}{\Omega^2} \right)^{1/4}. \tag{30}$$

Upon the thermal reaching the horizontal surface, it is expected to spread as a gravity current and become unstable to shed baroclinic eddies. As for the case of plumes, two cases can be considered.

(a) $z_c >> H$: For the simple case of a point thermal, the buoyancy of the thermal at the horizontal boundary can be estimated as

$$\beta \sim \left(\frac{q_T}{H^3} \right), \tag{31}$$

and the frontal propagation velocity is given by

$$\frac{dr}{dt} \sim (\beta h_g)^{1/2} \sim \left(\frac{h_g q_T}{H^3} \right)^{1/2}. \tag{32}$$

Since the characteristic height of the thermal at any frontal radius r can be estimated as $r^2 h_g \sim H^3$, it is possible to write

$$c = \frac{dr}{dt} \sim \left(\frac{q_T}{r^2} \right)^{1/2} \tag{33}$$

or

$$r^2 - r_0^2 \approx q_T^{1/2} t, \tag{34}$$

where r_0 is the impact radius of the thermal and t is the time elapsed after the impingement. The radius at which the gravity current becomes unstable can be evaluated as c/Ω or

$$r_c \approx c_5 \left(\frac{q_T}{\Omega^2} \right)^{1/4}. \tag{35}$$

(b) $z_c << H$: In this case the thermal growth is arrested by the rotation at z_c and it can be assumed that the buoyancy at $z = H$ is the same as that at $z = z_c$. The buoyancy of the thermal at the impingement is given by $(q_T \Omega^6)^{1/4}$, and thus

$$r_c \approx c_6 \left(\frac{q_T}{\Omega^2} \right)^{1/4}. \tag{36}$$

Laboratory experiments were performed by releasing either a turbulent plume or a thermal (made out of salty water) to a homogeneous (or a two-layer) fluid contained in a rotating tank. Standard flow visualization and particle-tracking systems were used to obtain information on the flow evolution. Plumes of different diameters were also considered to delineate the effects of the source diameter. In the former case, the starting plume sank into the underlying, less-dense, homogeneous layer of water forming a growing 3-D turbulent layer. When the turbulent front reached a transition depth z_c, the rotational effects became dominant and the lateral growth of the plume was found to be inhibited. Fluid motions appeared to be 2-dimensional in planes perpendicular to the axis of rotation. At this time, the descent of the plume was somewhat decelerated and 2-D vortex structures were found to form beneath the 3-D turbulent mixed layer. These vortices then penetrated downward to produce vortex columns. Once the plume reaches the bottom of the tank, it spread slowly along the bottom forming 2-D vortex columns. Figure 1 shows a plot of the frontal position versus time, using the non-dimensionalized parameters $h/(B/\Omega^3)^{1/4}$ and Ωt. Note the initial descent with 3/4 slope. Then when $h/(B/\Omega^3)^{1/4}$ is approximately 3.3 at $\Omega t = 2.3$, the slope decreases showing a change in speed of the starting plume cap. The corresponding variation of the width is shown in Figure 2. Note the complete arrest of the horizontal growth of the plume at a time $\Omega t \approx 5.5$. The calculated parameters based on the experiments are $\alpha_{zc} \approx 3.3$ and $\alpha_{bc} \approx 1.8$.

When the result $z_c = 3.3(B/\Omega^3)^{1/4}$ is applied to the ocean with typical values of B = 412 m^4s^{-3} and $\Omega = 7.14 \times 10^{-5}$ rads^{-1}, it is possible to get $z_c \approx 19$ km. This is obviously greater than the depth of the ocean, and hence the geophysically interesting case would be $H < z_c$. The observations made during the experiments with $H < z_c$ show that the plume impinges on the bottom of the tank and propagates horizontally as a gravity current, until it grows to a certain lengthscale, r_c. Thence the flow becomes baroclinically unstable and breaks up into isolated eddies. The critical radius r_c at which the eddies are shed was measured and was plotted as a function of $(B/(H\Omega^3))^{1/3}$; a forced fit line of slope one indicated $\alpha_g = 1.3$.

Some experiments were carried out in non-rotating fluids to investigate the effect of the source diameter on plume properties. According to (5), $h = (Bt^3)^{1/4} f_3(d_o/(Bt^3)^{1/4})$; and when do $\rightarrow 0$ or $d_o/(Bt^3)^{1/4} \rightarrow 0$ (large t), $h = \alpha_3 (Bt^3)^{1/4}$. On the other hand, when the source is

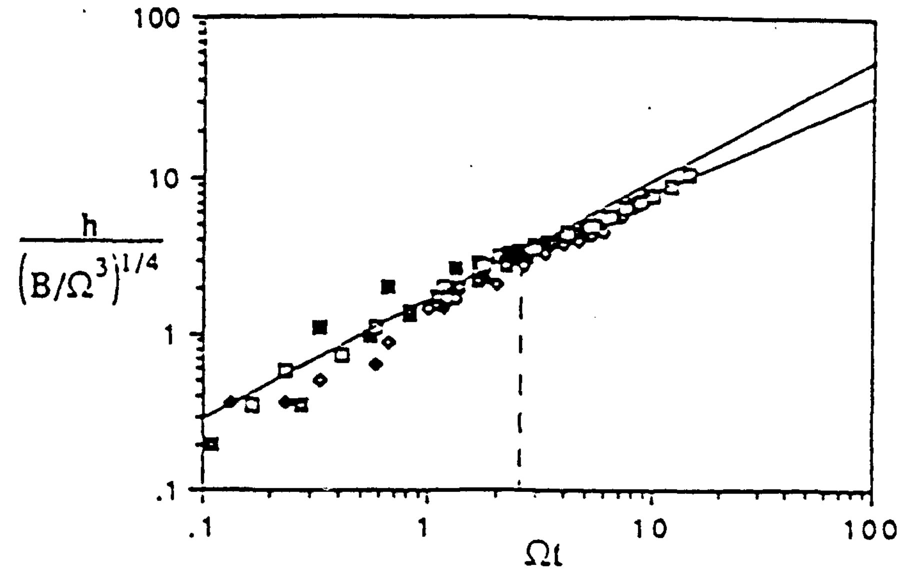

Figure 1: The variation of the vertical frontal position of the starting plume with time (non dimensional).

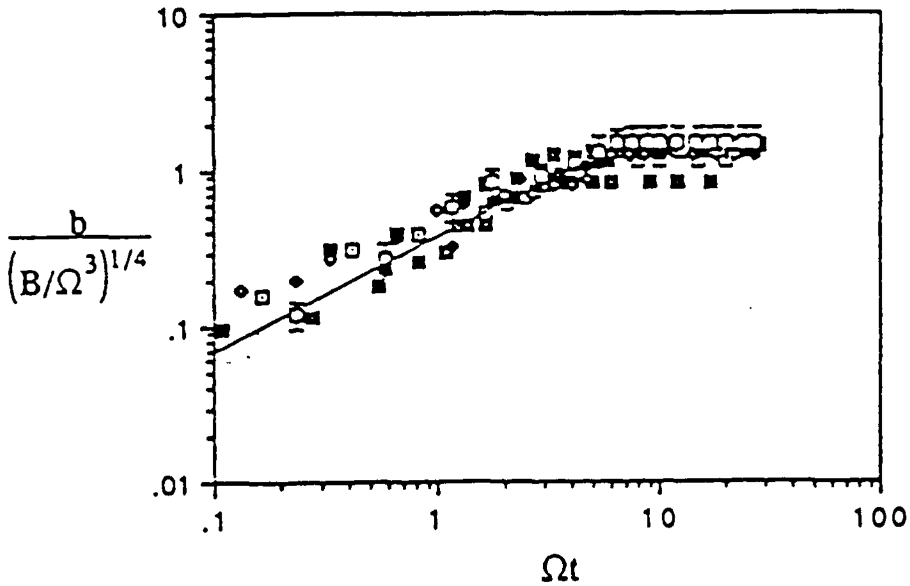

Figure 2: The variation of the width of the plume with time (non-dimensional).

homogeneous, the rate of descent becomes $h = \alpha_3^*(Bt^3/d_0^2)^{1/2}$ (second kind of self similarity when $d_0 \to \infty$). Thus we expect the characteristic descent law of the starting plume to change from $t^{3/4}$ to $t^{3/2}$ as the source diameter changes from $d_0 \to 0$ to $d_0 \to \infty$. In other words, a plot of $h/(Bt^3)^{1/4}$ should change from a constant α_3 in the limit $d_0 \to 0$ to $\alpha^*(Bt^3/d_0^4)^{1/4}$, when d_0 is increased.

Experiments were carried out with varying initial source diameters d_0, and the results were used to evaluate the condition under which the initial plume diameter can be neglected. The results for different d_0 values initially (at small t) followed $t^{3/4}$, but then clear departures could be seen. Accordingly, the point-plume source approximation is valid when the plume front satisfies $h > 11.7d_0$.

Experiments were also carried out to investigate the effect of d_0 on the propagation of gravity currents induced by the impingement of plume on the interface, in the presence of background rotation; as was discussed earlier, the radius at which the gravity current becomes unstable should be given by $r_c/(B/H\Omega^3)^{1/3} = f_7[d_0/H]$, when $H < z_c$. The results show that, when the initial diameter is unimportant, the non-dimensional critical radius is approximately $1.4(B/H\Omega^3)^{1/3}$. When d_0 becomes important at $d_0/H \approx 0.12$, the slope of the graph showed a decrease according to $r_c/(B/(H\Omega^3))^{1/3} = -29(d_0/H) + 5$.

3. Research on lead-Induced Convection

The polar ice cap often cracks and forms long, narrow channels of open water which are known as leads. These openings play an important role in the heat budget and circulation of polar oceans. In the winter the opening of a lead is associated with the onset of turbulent convection above and below the lead, because of the refreezing of surface water and rejection of heat into the atmosphere, respectively. Lead-induced convection is associated with a rich variety of fluid-dynamical phenomena, yet studying them in field situations is not easy due to the unpredictability of their occurrence and short resident times. As such, laboratory experiments and numerical models can play a major role in lead-related studies. The purpose of this study was to review the results of some previous laboratory experiments, which appear to be of importance in guiding and interpreting field experiments, and to carry out new laboratory experiments dealing with lead-induced motions.

To this end, laboratory experiments were carried out to investigate the interaction between turbulent line buoyant plumes and sharp density interfaces with the hope of using the results to interpret oceanic observations pertinent to crack openings in the polar ice cap (leads). The experiments were carried out by releasing a turbulent line plume (with buoyancy flux per unit length q_o) onto the surface of a two-layer fluid, and the evolution of the plume was monitored. The plumes initially descend as in a homogeneous fluid, impinge on the density interface, and then spread horizontally as gravity currents. The results are summarized below.

(i) The 'cap' of the starting plume initially descends as in a non-stratified fluid, and its position h and width b at a given time t is given by $h \simeq q_o^{1/3} t$ and $b \simeq 0.66\ h$. The half width of the plume that immediately follows the cap was found to be $\ell \simeq 0.16\ h$.

(ii) The evolution following the impingement of the plume cap on the density interface was found to be governed by the bulk Richardson number $Ri = \Delta b \ell_D / q_o^{2/3}$, where ℓ_D is the half width ℓ of the plume at the interface and Δb is the buoyancy jump across the interface. When $Ri > 10$, the plume cap was found to be separated into two hetrostrophic vortices, which travel a distance of $x_c = (3 - 4)\ell_D$, before starting their gravitational collapse. The resulting gravity current showed some similarities to those propagating over solid surfaces, such as K-H instabilities behind the head, but its nose angle was much steeper. When $Ri > 5$, the penetration of the plume into the lower layer was found to be small, of the order of the thickness of the interface. When $1 < Ri < 5$, the gravity current that is formed by the plume fluid rebounding off the distorted interface showed qualitative differences with the case $Ri > 10$. The vortex nature was weak within the current and the nose angle was close to the theoretical value predicted by the inviscid theory; however, no significant mixing was present at the bottom boundary. When $0.6 < Ri < 1$, mixing was prevalent between the gravity current and the surrounding fluid and the gravity current was symmetric with respect to the interface. At much lower Ri (< 0.5), the plume was found to penetrate deep into the interface, impact on the tank bottom, and spread horizontally while rising slowly.

(iii) The average depth δ of penetration of the plume into the lower heavy layer was found to be given by $\delta/\ell_D = 4\ \mathrm{Ri}^{-1}$, for $\mathrm{Ri} < 5$. At large Ri, this power law was closer to $\mathrm{Ri}^{-1/2}$; in this case δ is smaller than the interfacial thickness, and hence the penetration depth follows a different power law behavior than that of a two-layer fluid.

(iv) The outward-flowing gravity current generated by the plume impingement on the interface showed a constant velocity $U_f \simeq 0.95\ q_o^{1/3}$, for $\mathrm{Ri} > 5$. At low Ri, the result followed $U_f/q_o^{1/3} = 0.7\ \mathrm{Ri}^{0.17}$. The average thickness of the current is given approximately by $H/D = 0.28$ for data taken at $\mathrm{Ri} > 5$ and $H/D = 0.3$ for $\mathrm{Ri} > 1$.

(v) Associated with the outward-flowing current, there is an inward subsurface jet of velocity $U_i \simeq 0.25\ q_o^{1/3}$, for the entire Ri range investigated. The entrainment flow for the expanding plume is also provided by this jet.

(vi) When $\mathrm{Ri} < 20$, entrainment of heavy fluid from the lower layer into the plume impinging on the interface was evident. The result is the generation of a sub-interfacial horizontal current directed toward the region of impingement. The velocity of this current was found to be given by $U_b/q_o^{1/3} = 0.2\ \mathrm{Ri}^{-1/2}$; when this is expressed in terms of a vertical entrainment velocity U_e pertinent to the horizontal area of impingement, the entrainment law $U_e/q_o^{1/3} = 0.6\ \mathrm{Ri}^{-1}$ could be obtained. Additional entrainment can occur into the gravity current when $\mathrm{Ri} < 1$.

(vii) The impingement of the plume on the density interface generates interfacial waves of different frequencies. The dominant mode was found to be the lowest mode of internal waves.

The above experiments were extended to include the effects of background rotation by carrying them out on a rotating table. It was demonstrated that the leads-induced motions are affected by the background rotation after descending to a depth of $3.2(q_o/\Omega^3)^{1/3}$, where q_o is the surface buoyancy flux and Ω is the rate of background rotation. The width of the plume at this point is $1.1\ (q_o/\Omega^3)^{1/3}$. After some time, the plume becomes unstable at its transverse edges and deflects sideways, thereby producing a strongly three-dimensional cyclonic spiraling flow pattern.

4. Publications During the Contract Period

Journal Papers

Noh, Y. and Fernando, H.J.S., "A Numerical Study on the Formation of a Thermocline in Shear-free Turbulence," *Physics of Fluids*, **A3(3)**, 422-426, 1991.

Zangrando, F. and Fernando, H.J.S., "A Predictive Model for the Erosion of Thermohaline Interfaces," *ASME Journal of Solar Energy Engineering*, **113**, 59-65, 1991.

Fernando, H. J. S., Chen, R.-r. and Boyer, D. L., "Turbulent Thermal Convection in Rotating Fluids," *Journal of Fluid Mechanics*, **228**, 513-547, 1991.

Stegen, G.R., Muench, R.D., Fernando, H.J.S. and Ching, C.Y., "The Spatial/Temporal Evolution of Diffusive Thermohaline Layers," *Physics of Fluids A*, **3(5)**, 1142, 1991.

Stephenson, P.H. and Fernando, H.J.S. , "Laboratory Experiments on Turbulent Mixing Across Sheared Interfaces", *Physics of Fluids A*, **3(5)**, 1461, 1991.

Noh, Y. and Fernando, H.J.S., "Propagation of Gravity Currents Along an Incline in the Presence of Boundary Mixing," *Journal of Geophysical Research (Oceans)*, **96(7)**,12,586-12,592, 1991.

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Davies, P.A., Fernando, H.J.S., Besley, P. and Simpson, R., "The Generation and Spreading of a Turbulent Mixed Layer in a Rotating Stratified Fluid," *Journal of Geophysical Research (Oceans)*, **96(7)**, 12,567-12,585, 1991.

Stephenson, P.W. and Fernando, H.J.S., "Turbulence and Mixing in a Stratified Shear Flow," *Journal of Geophysical and Astrophysical Fluid Dynamics*, **59**, 147-164, 1991 .

Noh, Y. and Fernando, H.J.S., "The Motion of Buoyant Cloud Along an Incline in the Presence of Boundary Mixing," *Journal of Fluid Mechanics*, **235**, 557-577, 1992.

Lin, Q., Lindberg, W., Boyer, D.L. and Fernando, H.J.S., "Linearly Stratified Flow Past A Sphere," *Journal of Fluid Mechanics*, 240, 315-354, 1992.

De Silva, I. P. D., and Fernando, H. J. S., "Some Aspects on Mixing in a Stratified Turbulent Patch," *Journal of Fluid Mechanics*, **240**, 601-625, 1992.

Noh, Y., Fernando, H.J.S. and Ching, C.Y., "Flow Induced by the Impingement of a Thermal on A Density Interface," *Journal of Physical Oceanography*, **22(10)**, 1207-1220, 1992.

Lin, Q., Boyer, D.L. and Fernando, H.J.S., "Turbulent Wakes of Linearly Stratified Flow Past a Sphere," *Physics of Fluids A*, **4(8)**, 1687-1696, 1992.

Noh, Y. and Fernando, H. J. S., "The Influence of Molecular Diffusion on the Deepening of the Mixed Layer," *Dynamics of Atmospheres and Oceans*, **17**, 187-215, 1993.

Noh, Y. and Fernando, H.J.S., "A Numerical Model for the Fluid Motion at a Density Front in the Presence of Background Turbulence," *Journal of Physical Oceanography.*, **23(6)**, 1142-1153, 1993.

Fernando, H.J.S. and De Silva, I.P.D., "Note on Secondary Flows in Oscillating-Grid Mixing Box Experiments," *Physics of Fluids A* , **5** (7), 1849-1851, 1993.

Fernando, H.J.S. and Ching, C.Y., "Effects of Background Rotation on Turbulent Line Plumes," *Journal of Physical Oceanography,* **23,** 2125-2129, 1993.

Fernando, H.J.S. and Ching, C.Y., "Lead-Induced Convection: A laboratory Perspective," *Journal of Marine Systems* , **4.**, 217-230, 1993.

Lin, Q., Boyer, D.L. and Fernando, H.J.S., "Note on Internal Waves Generated by the Turbulent Wake of a Sphere," *Experiments in Fluids* , **15**, 147-154, 1993.

Noh, Y. and Fernando, H.J.S., "The Transition in the Sedimentation Pattern of a Particle Cloud," *Physics of Fluids A* , 5 (12), 3049-3055, 1993.

Ching, C-Y., Fernando, H.J.S. and Noh, Y., Interaction of a Negatively Buoyant Line Plume with a Density Interface," *Dynamics of Atmospheres and Oceans*, (Accepted for Publication).

Davies, P.A., Boyer, D.L., Fernando, H.J.S. and Zhang, X., "On the Unsteady Motion of a Circular Cylinder Through a Linearly Stratified Fluid," *Philosophical Transactions of the Royal Society (London)* (Accepted for Publication).

Flor, J., Fernando, H.J.S. and Van Heijst, G.J.F., "The Evolution of an Isolated Turbulent Region in a Two-Layer Fluid," *Physics of Fluids* (Accepted for Publication).

Lin, Q., Boyer, D.L. and Fernando, H.J.S., "Flows Generated by the Periodic Horizontal Oscillations of a Sphere in a Linearly Stratified Fluid," *Journal of Fluid Mechanics* (Accepted for Publication).

Perera, H.J.S., Fernando, H.J.S. and Boyer, D.L., "Wave-turbulence Interaction at an Inversion Layer," *Journal of Fluid Mechanics*, (Accepted for Publication).

Lin, Q., Boyer, D.L. and Fernando, H.J.S., "The Vortex Shedding of a Streamwise-Oscillating Sphere Translating Through a Linearly Stratified Fluid," *Physics of Fluids* (Accepted for Publication)

DeSilva I.P.D. and Fernando, H.J.S., "Oscillating Grids as a Source of Nearly Isotropic Turbulence" *Physics of Fluids*. (Accepted for Publication)

Perera, M.J., Fernando, H.J.S. and Boyer, D.L., "Mixing Induced by the Oscillatory Flow Past a right Circular Cylinder," *Journal of Fluid Mechanics* (Accepted for Publication).

Papers Submitted

Fernando, H.J.S., van Heijst, G.J.F. and Fonseka, S.V., "The Evolution of an Isolated Turbulent Region in a Stratified Fluid," *Journal of Fluid Mechanics*, (under revision).

DeSilva I.P.D. and Fernando, H.J.S., "The Collapse of a Turbulent Mixed Region in a Stratified Fluid," *Journal of Fluid Mechanics* (under revision).

Ayotte, B.A. and Fernando, H.J.S., "The Motion of a Turbulent Thermal in the Presence of Background Rotation," *Journal of Atmospheric Sciences* (Under revision).

Davies, P.A., Mofor, L.A., and Fernando, H.J.S. "Laboratory Studies of Mixed Buoyant Jets in Shallow CrossFlows" *Transactions of the Institute of Civil Engineers*, U.K (Under revision)..

Fernando, H.J.S. "Migration of Density Interfaces Subjected to Differential Turbulent Forcing". Submitted to *Journal of Geophysical & Astrophysical Fluid Dynamics*.

Bermzn, N.S., Boyer, D.L., Brazel, A.J., Brazel, S.W., Celada, R.A., Chen, R-r, Fernando, H.J.S., Fitch, M.J., and Wang H-w. "Synoptic Classification and the Design of Physical Model Experiments for Complex Terrain," Submitted to *Journal of Applied Meteorology*

Papers in Preparation

Fernando, H.J.S. and Hunt, J.C.R. "Turbulent Mixing Across Shear Free Density Interfaces; Part 1 - Modeling Considerations," Submitted to *Journal of Fluid Mechanics*

Fernando, H.J.S., McGrath, J. and Hunt, J.C.R. "Turbulent Mixing Across Shear Free Density Interfaces; Part 2 - Laboratory Experiments," Submitted to *Journal of Fluid Mechanics*

Fernando, H.J.S., Mofor, L., Davies, P.A. and Ching, C.Y., "Interaction of Multiple Line Plumes in an Uniform Environment,"

Fernando, H.J.S., Ching, C.Y. and Stegen, G.R., "Some Aspects of the Evolution of Thermohaline Staircase Structures,"

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